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AUTHOR Vosniadou, Stella
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ABSTRACT

Recent research in cognitive science and science education suggests that science-naive individuals have an understanding of the natural world based on their interpretation of everyday experience. This can make the process of conceptual change difficult. This paper presents ideas related to the acquisition of knowledge in astronomy. A theoretical framework based on research is discussed in detail. Implications for instruction discussed include knowledge of children's experiential beliefs and an understanding of the interdependencies among various concepts that comprise a domain in which knowledge is to be acquired. The document concluded that children are commonly not provided with adequate explanations of the concepts to be acquired and that instruction is not sensitive to the order of acquisition of these concepts. (CW)

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Knowledge Restructuring and Science Instruction

Stella Vosniadou

University of Illinois at Urbana-Champaign and Aristotelian University of Thessaloniki (Greece)

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Knowledge Restructuring and Science Instruction

One of the most interesting results of recent work in cognitive science and science education has been the realization that science-naive individuals have an understanding of the natural world which is based on their interpretation of everyday experience. This intuitive knowledge is usually quite different from the scientific knowledge which is expected from literate adults in our society. In the process of learning science students must change their intuitive knowledge to make it conform to the currently accepted scientific knowledge. The process of conceptual change can be a rather lengthy and difficult one because intuitive ideas appear to be quite robust and difficult to extinguish (e.g., diSessa, 1982; Driver & Easley, 1978; Novak, 1977; Osborne & Wittrock, 1983; White, 1983).

There is currently a lot of debate about how it is best to characterize the nature of intuitive knowledge and the mechanisms thereby which it can be modified (Vosniadou & Brewer, 1987). Some researchers believe that novices' ideas can be conceptualized as consisting of a coherent and systematic set of ideas which have a status similar to that of a scientific theory. In some cases these ideas are found to resemble earlier theories in the history of science (McCloskey, 1983; Wiser & Carey, 1983). Other researchers think that naive physics consists of a fragmented collection of ideas which are loosely connected and do not have the systematicity that one attributes to a scientific theory (diSessa, 1985).

Depending on one's beliefs about the nature of intuitive knowledge different instructional implications are drawn. Researchers who view novices as having relatively well organized and consistent naive theories think that the process of science learning requires a change in theory similar in some respects to the kind of theory change observed in the history of science (Hanson, 1958; Kuhn, 1962; 1970). Although the mechanisms for achieving this kind of theory change are not yet known, most of these researchers believe that it is necessary to confront the novice students with enough evidence to make them realize the limitations of their theories and change them (Anderson, 1977; Collins, 1986; McCloskey, 1983; Nussbaum & Novick, 1982).

On the contrary, diSessa (1985) thinks that a one-by-one attack of the knowledge fragments that constitute intuitive physics is a hopeless task. He suggests that what is needed is to use these fragments to develop the scientific understanding that a science-naive individual lacks. diSessa proposes developing ways to collect and unify intuitive knowledge through microworlds.

Advances in instruction require some clarification of these conceptual issues. In this paper we will advance an intermediate position based on our research of the acquisition of knowledge in astronomy and will draw the implications of this position for instruction.

Our Theoretical Framework

Our theoretical ideas have been derived from our research on the process of knowledge acquisition in the domain of astronomy. We have conducted a series of experiments investigating children's and adults' knoweldge of the domain of astronomy. These studies have involved preschool, elementary, and high school children, college undergraduates and adult illiterates (Brewer, Hendrich, & Vosniadou, in press; Vosniadou, 1987; Vosniadou & Brewer, 1987; Vosniadou & Brewer, in press). In addition to studies conducted in the United States, we have collected data from children and adults in India, Samoa and Greece. These studies have provided us with specific information about children's and adults' knowledge about the shape, gravity, movement, temperature, composition, relative size and relative location of the earth, the sun, the moon and the stars, as well as explanations of phenomena like the day/night cycle, the seasons, the phases of the moon, and the eclipses of the sun and the moon.

Our studies have shown that children construct an understanding of the physical world which becomes continuously modified with exposure to adult ideas. We have adopted the construct of the mental model to characterize this understanding. Unlike scientific theories, mental models are assumed to be incomplete and unstable systems which are continuously modified. Nevertheless, these knowledge structures do not lack some coherence and systematicity. Because they are constructed on the basis of an individual's experience with the physical world they come to mirror many of the constraints of this world. These constraints serve to give a mental model some predictive power. An individual with a mental model of a domain has the ability to answer questions about the

domain by "running" the model (see Collins & Gentner, 1987; Gentner & Stevens, 1983; Stevens & Collins, 1980). Thus a child who has a phenomenal model of the day/night cycle according to which the sun goes behind the mountains can answer a generative question such as "Where is the sun during the night?"

Our experiments have shown that there is a range of mental models that children and adults can have of concepts such as the earth's shape, size, movement, and location, and of phenomena such as the day/night cycle, the seasons, and the phases of the moon. For example, in the case of the earth shape concept we have identified six different mental models held by elementary school children. As Table 1 shows, some children think that the earth is shaped like a square or a rectangle while others think the earth is circular but flat (like a pancake). Some children know that the earth is round but think that we live in the flat middle of the round earth, while others think that we live on the flat top of a truncated sphere or on the top of the sphere (questionable sphere).

Similarly, elementary school children hold one of a number of different models of the day/night cycle (see Table 2). Some children believe that the change from day to night is caused because the sun moves down and the moon moves up, while others think that clouds move in front of the sun and block it. Some children know that the day/night cycle is caused by the earth's axis rotation. One interesting model is held by children who know that the earth rotates around its axis but attribute the day/night cycle to the presence of the moon. These children think that the moon is fixed in some place in the sky where it is always night; as the earth rotates our part of the earth eventually comes to face the moon and as a result to bring the night.

Children's models of the various concepts investigated were identified from their responses to a number of questions tapping each concept. In an effort to understand as accurately as possible children's concepts, we included three types of items in our questionnaires: (1) factual questions designed to test the child's knowledge of theoretically important facts (e.g., "What is the shape of the earth?"), (2) explanation questions, designed to lead the child to explain these facts (e.g., "How do you know that the earth is round when the earth around us appears to be flat?"), and (3) generative questions, designed to capture the child's generative model (e.g., "If you were to walk for many days

would you ever reach the end of the earth?"). Follow-up questions and confrontation questions were also used throughout the interview to try to understand children's beliefs.

Children gave a variety of responses to these questions. For example, some children said that the shape of the earth is a "rectangle," others a "circle," others "round." Some children said that there is an end to the earth, others that there is no end, and others that there is an end but that it cannot be reached because it is high up. Some children said that you look "down" to see the earth, some that you look "up." In many cases children's responses seemed to be internally inconsistent. For example, the same child who said that the earth is round could also claim that the earth has an end and that people can fall down from that end.

We were interested in determining whether children's responses to our questions were determined by some kind of underlying conceptual model and to the degree to which they were internally consistent with respect to that model. To do that we derived from our data as well as from previous research in this area (e.g., Nussbaum & Novak, 1976; Nussbaum, 1979; Sneider & Poulos, 1983) a number of possible models for each concept. Then, for each question investigating a given concept we generated the answers expected if the children had that model. For example, we reasoned that if the children believed that the earth is a sphere, they should say that the earth's shape is "round," that you look "down" to see the earth, that there is no edge to the earth, and that if you were to walk for many days in a straight line you would eventually come back to where you started.

Once the pattern of responses for each model was determined, we checked children's responses to the relevant questions to see if they agreed with the expected ones. Placement in one of the models required no more than one deviation from the expected pattern and only if this deviation occurred in a non-defining item for that category. For example, a child who said that there is an end to the earth could not be assumed to have a spherical earth concept, even in those cases where this response was the child's only deviation from a spherical earth concept response pattern. On the other hand, the response "circle" to the question "What is the shape of the earth?" was considered an acceptable deviation for a child whose responses agreed in all other respects with the spherical earth concept.

We were able to determine children's models for about 80 to 85% of the cases for each concept investigated. Some children had mixed models which contained elements from 2 or 3 individual models and in a few instances no consistent model could be identified. These results suggest that there is a relatively high degree of internal consistency in children's ideas at the level of the individual concepts investigated (e.g., shape, movement, size, and location of the earth, sun, moon, and stars, etc.). This consistency drops when more than one concept are examined together, but we do not have the results from this analysis yet.

Once these models were identified, we realized that they could be grouped in three distinct categories: Phenomenal, assimilatory and scientific. The defining characteristic of phenomenal models is that they require as little deviation as possible from the natural world as is phenomenally experienced. They show no influence from adult scientific models. Thus, young children believe that the earth is shaped like a rectangle or like a square and that it does not move, that the day/night cycle is caused by the movement of the sun or by the movement of the clouds blocking the sun, that stars are small objects, and that things fall down when you drop them.

Scientific models are the models held by educated adults in our society, the models that agree with current scientific views. Assimilatory models show a combination of phenomenal and scientific views, such as the view that the earth is round like a pancake, or that we live in the flat middle of a spherical earth. Other examples of assimilatory models are the view that night is associated with the moon regardless of the earth's axis rotation, and the view that the stars like the moon take their light from the sun. What all of these models have in common is an attempt to reconcile adult scientific views with phenomenal models of the earth, the sun, the moon and the stars.

The presence of assimilatory models clearly demonstrates that the process of changing a phenomenal model to a scientific one does not involve a sudden and dramatic restructuring but that it is slow and gradual. In addition, assimilatory models provide interesting information about the nature of the phenomenal models from which they are formed. More specifically, they suggest that phenomenal models are composed of a set of smaller and more fundamental units of intuitive knowledge, which we have called experiential beliefs. Thus, the phenomenal model of the flat earth is

based on the experiential beliefs (among others) that the ground is straight, that there is an end to the earth, that things fall down when you drop them, that the sky is located above the earth, that there is ground or water all the way down to the end of the earth, etc.

In forming assimilatory models, children change their phenomenal models but do that in a way that allows them (1) to retain all or some of their experiential beliefs, and (2) without contradicting adult teachings. For example, the children who change their phenomenal models of a rectangular earth to the assimilatory model of a pancake earth have retained almost all of the experiential beliefs that gave rise to the phenomenal model. These children answer our questions in a way that shows that they still believe that the earth is flat, that it has an end, that there is ground all the way down and that the sky is above the earth. The only belief they have changed is that the edges of the earth consist of straight lines and thus that the earth is shaped like a rectangle or like a square.

A detailed examination of children's responses reveals that there is a progression of more and more advanced assimilatory models depending on how many experiential beliefs children have given up. For example, the inside the sphere assimilatory model of the earth shape is a more advanced one than the pancake model. The children who hold the inside the sphere model have given up on their experiential belief that the earth is flat, that there is ground all the way down, and that the sky is only on top of the earth. These children conceptualize the earth as a sphere suspended in space but still believe that the people live on flat ground inside the earth, and that things fall downward (and therefore people cannot live at the bottom of the earth). Similarly, the children who think that night is caused because the earth's rotation allows our side of the earth to find the moon, have not yet given up on their experiential belief that night is located in some place in the sky where the moon is, although they have changed their experiential beliefs that the earth does not move but the moon does.

The formation of assimilatory models is reinforced by the nature of science instruction. Children are almost never told why the earth that appears to everyone to be flat is really a sphere, or how it is possible for the earth to move around itself when we do not feel it. By presenting counterintuitive information as a fact, we create the preconditions for a misconception to be formed.

In order to understand how misconceptions are formed, it is necessary to assume that children consider their experiential beliefs to be unquestionable truths about the way the world is, truths that are obvious to everyone. Experiential beliefs are not like a hypothesis or an assumption in a scientific theory, and this is another way in which a phenomenal model differs from a scientific theory. Children must also consider these truths to be obvious to adults, something that explains why they do not question the adults about the truth of their statements regarding the shape, movement, size, etc. of the earth that run counter to their phenomenal models.

We think that the genesis of a misconception can be conceptualized in the following way. When children with a phenomenal model of a flat and stationary earth read in a book or hear from an adult that the earth is "round like a ball," they do not want to believe that the adult is wrong but cannot reconcile this information with their experiential belief of a flat earth. Because they consider this experiential belief to be such an obvious truth about the world, they think that they have misunderstood what the adult means by these statements. In trying to interpret this information in a way that does not contradict their experiential beliefs, children construct assimilatory models or remain confused.

Implications for Instruction

Our work suggests that in order for instruction to be successful in moving children from their phenomenal models to current scientific models it must be based on a thorough understanding of children's experiential beliefs as well as on an understanding of the interdependencies among the various concepts that comprise a domain in which knowledge is to be acquired.

Knowledge of children's experiential beliefs is necessary because different instructional methods may have to be employed when the knowledge acquisition process requires changing these beliefs than when it does not. For example, one would expect preschool children to understand that the sun is round by simply being told so (young children think that the sun is circular but flat). We know, however, that telling children that the earth is round like a ball does not result in an immediate understanding of the earth's shape. In those cases where an adult scientific concept contradicts children's experiential beliefs, these contradictions must be pointed out by the adult. In addition, the

children must be provided with persuasive reasons for questioning their experiential beliefs and with an explanatory framework to replace the one they currently have. The success of instruction will depend on how well our basic research has done the job of uncovering all of the experiential beliefs that cause misconceptions and in discovering the appropriate instructional methods for changing them.

Finally, instruction must be also based on knowledge of the interdependencies among concepts that comprise a domain because these interdependencies determine to a large extent the order of acquisition of these concepts. We believe that instruction that utilizes the information about the order of acquisition of the concepts that comprise a given domain will be much more effective than instruction which does not.

A limited look at some astronomy instruction in local schools and a detailed examination of the astronomy units in four leading science series that we have recently undertaken have revealed problems in both areas. For example, in one series examined, the authors organized the material to be acquired around scientific information about the moon, the sun, and the earth. Therefore, they included a unit on the moon at grade one which takes the children from a description of the size and shape of the moon to an explanation of the moon's phases (which most of our adult subjects cannot explain), ignoring children's models and before providing any instruction on the relative size and location of the earth, the sun and the moon in the solar system.

As expected, no explanations were provided of concepts like the shape, movement, size and location of the earth. In all cases, the children were simply told that "the earth is like a globe" and that "it rotates around its axis," that it is smaller than the sun, and so on. Whenever explanations were provided, they were incomplete and inadequate both because they did not address all of the underlying experiential beliefs that can give rise to misconceptions and because they did not take into consideration the order of acquisition of conceptual knowledge in this domain.

In one experiment we have recently conducted we tested third graders' understanding of the day/night cycle before and immediately after they read a two-page text from a leading science series on the day/night cycle written for their grade level (Vosniadou & Samarapungavan, in preparation).

The results were rather revealing. Out of the 23 children investigated, 6 provided adequate explanations of the day/night cycle (e.g., in terms of the axis rotation of the earth) before they read the text and 5 after they read it! These numbers actually include two children who became confused after reading the text and thought that the day/night cycle is caused by the earth's revolution around the sun, rather than by its axis rotation and one child who actually changed from a model of a moving sun and moon to that of a moving earth.

There were two main reasons for children's failures to understand the text. First, many of the third-grade children did not have an adequate earth shape concept in the first place and as a result they could not understand the information about the earth's movement or could not see how this movement could explain the day/night cycle. For example, a child with a pancake earth model had interpreted the information about the earth's axis rotation to mean that the pancake earth turns around. This movement cannot, however, explain the day/night cycle and the child was obviously confused.

Second, many children who understood how the earth moves formed the assimilatory model previously mentioned according to which the earth's axis rotation causes the earth to face the moon and thus to cause the night. These children said that the moon does not move, and answered our generative question "What changes do we need to make to have day time all the time?" by saying that "We must get rid of the moon!" Needless to say, an adequate explanation of the day/night cycle must include not only information about the shape and movement of the earth, but also about the movement, shape, size, location and light of the sun, the moon, and the stars.

We are currently in the process of designing such an instructional unit paying particular attention to the sequence of concepts to be explicated and the nature of the proposed explanations for changing the experiential beliefs associated with each concept.

Conclusions

We have argued that our investigations of the process of knowledge acquisition in the domain of astronomy have shown that children construct phenomenal models of the observed world which require as little deviation from the world as phenomenally experienced as possible. These

phenomenal models are formed out of a smaller set of experiential beliefs, such as that stars are small objects, that things fall down when you drop them, that light is perceived directly, and that matter is solid.

Our research has shown that conceptual change will not necessarily come by attacking children's phenomenal or assimilatory models. Such models are easy to change. What is difficult is to change the experiential beliefs that give rise to them. While children should be made aware of these experiential beliefs and the internal contradictions among them, this will not by itself bring about the desired conceptual change either. Children must be provided with a different explanatory framework to replace their experiential beliefs and, furthermore, this should be done in a way that does not violate the relational structure of the domain in which knowledge is to be acquired and the interdependencies among the concepts that comprise it. This does not appear to be the kind of instruction elementary school children in the United States currently receive.

Our investigations of astronomy instruction and the astronomy units in four leading science series clearly demonstrate that children are not provided with adequate explanations of the concepts to be acquired and that instruction is not sensitive to the order of acquisition of these concepts.

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Table 1

Frequency of Earth Shape Models as a Function of Grade

Earth Shape Models	Grade 1	Grade 3	Grade 5	TOTAL
1. Sphere	2	8	10	20
2. Questionable Sphere	1	3	6	10
3. Inside the sphere	2	4	4	10
4. Pancake	0	1	0	1
5. Two-Earths	7	2	0	9
6. Flat	1	0	0	1
7. Mixed	7	2	0	9
TOTAL	20	20	20	60

Table 2

Frequency of Occurrence of the Various Day/Night Models

Responses	Grade 1	3	5	TOTAL
1. Earth rotates around its axis	2	4	12	18
2. Sun moves up/down and trades place with moon	13	3	0	16
3. Something blocks the sun	1	2	1	4
4. Earth rotates around its axis and sun and moon fixed	0	3	1	4
5. Mixed: Earth rotates and sun moves and clouds block sun	2	3	4	9
6. Sun revolves around Earth	0	1	0	1
7. Earth revolves around sun	0	2	2	4
8. Earth goes in orbit	0	1	0	1
9. No explanation	0	1	0	1
10. Undetermined	2	0	0	2
TOTAL	20	20	20	60